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OMEGA: A NEW COLD X-RAY SIMULATION FACILITY FOR THE EVALUATION OF OPTICAL COATINGS[*,**]

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ABSTRACT

We report on recent progress for the development of a new cold X-ray optical test capability using the Omega Facility located at the Laboratory for Laser Energetics (LLE) at the University of Rochester. These tests were done on the 30 kJ OMEGA laser at the Laboratory for Laser Energetics (LLE) at the University of Rochester, Rochester, NY. We conducted a six-shot series called OMEGA II on 14 July 2006 in one eight-hour day (supported by the Defense Threat Reduction Agency). The initial testing was performed using simple protected gold optical coatings on fused silica substrates. PUFFTFT analyses were completed and the specimen's thermal lateral stress and transverse stress conditions were calculated and interpreted. No major anomalies were detected. Comparison of the pre- and posttest reflective measurements coupled with the TFCALC analyses proved invaluable in guiding the analyses and interpreting the observed damage. The Omega facility is a high quality facility for performing evaluation of optical coatings and coupons and provides experience for the development of future National Ignition Facility (NIF) testing.

Introduction

We report first test results for the development of a new cold X-ray optical test capability using the Omega Facility located at the Laboratory for Laser Energetics (LLE) at the University of Rochester. Omega produces cold X-ray environments through the interaction of intense pulsed laser radiation with a target medium, e.g., germanium-loaded silica aerogels[1,2]. The X-ray environment (spectrum, pulse-width, and fluence) generated can be used to simulate relevant X-ray effects in materials and components. The team is developing the facility and verification protocols for use in the testing and validation of optical coatings/components designs and technology that support the Missile Defense Agency's (MDA) Ballistic Missile Defense System (BMDS)[3]. The experience from the Omega test series supports future National Ignition Facility test protocol development.

Specifically, the team is performing experiments on simple protected gold specimens to determine the response and damage modes and levels when exposed to the Omega environment. These results will be compared to those generated using other simulation facilities and analyses performed with other relevant environments. Tests were successfully performed in July 2006 which produced both damaged and undamaged specimens. This paper will present an overview of the testing and the test results.

Facility and Source Characterization

The X-ray output (spectrum, pulse width, and fluence) generated by the Omega facility is dependent upon a number of factors including:

- Laser power and pulse width/distribution
- Laser-target material, density, size, and configuration
- Distance and orientation from the source to test specimen

Figure 1 shows a typical spectrum measured during the July 2006 test series (known as Omega II) compared to 0.5 and 1 keV blackbody sources and the argon spectrum from the Double Eagle soft X-ray (SXR) facility. The raw Omega II spectrum contains significant low energy UV and X-ray components. This low energy radiation is generally undesirable from an optics standpoint since it complicates the analyses (the cross-sections below 0.1 keV are difficult to fit accurately) and it may artificially create damage in outer layers not expected in other cases. This low energy radiation can easily be filtered out using thin beryllium foil filters. The Omega II tests were mostly conducted using 1 and 2 mil beryllium foil filters. This not only eliminates the undesirable low energy radiation but also protects the specimen's optical surface from potential damage from debris generated by the facility. The Omega facility is, however, remarkably debris-free and a test was conducted to quantify the effect of the raw environment upon the optical properties. As shown in the figure, the filtered Omega II environment is a good match to low energy blackbodies. The Double Eagle (DE) argon spectrum shown was filtered by both a kimfol UV filter and a 3 mil beryllium foil filter to eliminate all of the transmitted radiation below about 3 keV. The vapor created by the Kimfol and the DE-generated metallic debris requires a thicker beryllium filter to provide a clean specimen environment. This provides some limit to the ability to simulate adequately some X-ray spectra such as a 0.5 keV blackbody.

Preliminary flux-time profiles for the Omega II tests are shown in Figure 2. These were measured by Sandia National Laboratories using a PCD filtered with an 8-mil Kapton layer. This provides a measure of the time-dependence of the lower energy X-ray component. The two flux-time pulses are significantly shorter than the typical Double Eagle argon dependency, also shown in Figure 2 for comparison.

The total X-ray yield available as measured in Omega II was between 100 and 225 calories. About one-third of that is transmitted through the 1 mil beryllium foil thickness. Experiments can be performed at ranges between 15 and 80 cm. This means that fluences in the range of 0.005 to 0.35 cal/cm^2 are available on the optical specimen. This fluence range combined with the measured spectrum and short pulse widths is acceptable for testing to failure of almost every coating concept currently being considered.

Test Specimens

Simple protected gold mirror specimens were tested in Omega II to maximize the team's understanding of the X-ray interaction with the materials and to simplify the initial experiment. The specimen design consisted of a 0.2 cm thick silica (SiO_2) substrate, a 2000 Å thick gold reflective layer, and a 400 Å thick SiO_x protective coating. The specimens were fabricated and characterized by Surface Optics Corporation (SOC) of San Diego, CA. SOC measured the reflectivity of a number of points on the surface of each sample between 200 and 2000 Å. Figure 3 shows the pretest measurements compared to a TFCALC reflectance calculation. The measurements were repeated after the specimens were exposed to the Omega radiation environment. The comparison between the pre- and post test reflectivities was used to determine the mirror degradation as a function of exposure level. Previous experience has indicated that coating systems show damage degradation in the visible wavelengths before the IR region.

Test Description

These tests were done on the 30 kJ OMEGA laser at the Laboratory for Laser Energetics (LLE) at the University of Rochester, Rochester, NY. We conducted a six-shot series called OMEGA II on 14 July 2006 in one eight-hour day (supported by the Defense Threat Reduction Agency). The following test matrix was developed to evaluate the mirror coating hardness as will as evaluate the beryllium filter requirements.

Testing Results

Six specimens were exposed during the one day test series conducted in July 2006. One optical mirror specimen was exposed on each of six shots. Table 1 provides the experiment details of the six shots. The yield was determined by integrating the LLNL-measured spectra. The uncertainties associated with the yields was estimated to be on the order of ±11%.

The fluence and spectrum incident upon the specimen front surface was determined by transporting the measured environments through a 99.86%-pure beryllium foil. The composition of the foil was determined from previous elemental analyses performed on similar materials which were used in previous underground tests.

Test Observations

Photographs were taken posttest during cassette disassembly at GH Systems. These show the cassette, specimens, and filters after X-ray exposure and testing and provide documentation of the disassembly procedure. Posttest photomicrographs of the specimens were taken at the ATK MR&TS Longmire Laboratory using an Olympus microscope with a Normarski set-up and an Olympus C-3030 camera. The photomicrographs have been examined and Table 2 indicates the condition of the coatings and substrates as determined by visual observations of the photos by GH Systems personnel. The visual observations showed no sign of melt of either the SiO_x or gold layers. However, it appeared that the parts of the exposed region of the SiO_x layer were removed from several of the specimens due to mechanical effects.

Figure 4 shows one of the photomicrographs for Specimen 1 which was exposed on Shot 52 (which was tested without a filter). It exhibited the most damage – complete removal of the SiO_x coating over the exposed area. The edge region suggests that the material was removed by mechanical means rather than coating melt. Figures 5 and 6 present posttest photomicrographs of Specimen 8 (Shot 56) which showed SiO_x removal over several areas. Figure 6 is a close-up of one of those areas which shows that the silica coating has actually folded back upon itself – a strong indication of mechanical failure of hot material. Figure 7 presents a photomicrograph of Specimen 5 (Shot 54) which showed no visual damage.

<u>Post Test Optical Measurements</u>

Posttest reflectance measurements on the tested and spare (untested) specimens were performed by Surface Optics Corporation. In addition, GH Systems performed TFCALC calculations to compare with the measured data. Figure 8 presents the pre- and posttest reflectance measurements on Specimen 3 which was untested and therefore should show no X-ray exposure effects, but should show any degradation due to handling or storage. Note that the posttest measurements were performed from 300 to 3000 nm rather than down to 200 nm as for the pretest measurements. There is essentially no difference between the pre- and posttest measurements and the TFTCALC calculations show good correlation with the data above 300 nm.

Figure 9 shows the reflectance measurements and TFCALC analyses for Specimen 1 (Shot 52) which was the unfiltered shot which showed complete removal of the silica protective coating. The posttest measurement shows an increase in the reflectance below about 800 nm. A TFCALC analysis was performed without the 40 nm silica protective coating which shows good correlation with the posttest measurement. This confirms that the silica coating was completely removed and that the removal did not affect the reflectivity of the gold layer.

Figure 10 shows the reflectance measurements and TFCALC analyses for Specimen 8 (Shot 56). This specimen showed partial removal of the silica protective layer. The posttest measurement shows an increase in the reflectance below about 500 nm. It would appear that perhaps about 15% of the silica coating was removed. Again, there appears to be no degradation in the reflectance of the gold layer.

Posttest Analyses

PUFFTFT[4] analyses[5] were performed to determine the temperature, lateral stress, and transverse (through-the-thickness) stress conditions in each of the tested specimens.

The models used were developed by Newlander and Childs[6]. The SiO_x coating model used was that developed for fused silica (Corning 7940) and may contain significant uncertainties. Few thermophysical properties are available for thin film coating materials. The calculations used the spectra provided by LLNL and piece-wise linear fits to the SNL-provided flux-time profiles. The fluences used were the nominal based upon the yield determined by the integration of the LLNL spectra and ±11% uncertainties to represent the extremes based on the data reduction techniques. All of the calculations showed that the nominal fluence gave peak temperatures in the gold layer very near or exceeding the gold melt temperature. These temperatures are reduced when the lower limit (-11%) of the fluence is used. Since no gold melt was observed, it is suspected that the nominal fluences may be somewhat too high. Figure 11 shows the calculated peak temperature envelope for Specimen 1 (Shot 52) which was fielded unfiltered. Here the peak temperature in the gold is 1026^{o}C, which is very near the gold melt of 1064^{o}C. Decreasing the fluence by 11% generates a lower peak temperature of 931^{o}C.

The lateral stresses are those stresses induced by expansion of the heated layers in the lateral direction (i.e. along the face of the mirror). The differential expansion of the layers will generate shear stresses along the interface as well as compressive or tensile stresses within the layer which may lead to damage or fracture within the material layer. PUFFTFT can be used to estimate these lateral stresses. Figure 12 shows the calculated lateral stress response in the layers for Specimen 1 at various times. The gold layer yields and goes into reverse yield during later times as the layer cools. The stress difference between the SiO_x and gold, and the gold and fused silica substrate are large (>0.5 kbars). However, calculations for Specimen 6 (Shot 53) showed stress differentials exceeding 0.75 kbars. There was no damage observed for that specimen. The lateral stress analyses suggest that the removal of the silica protective layer was not the result of excessive shear stresses unless there is a very large specimen-to-specimen variation. Because all of the specimens were processed and fabricated in the same manner and coated in one batch it is doubtful that these variations occurred.

Calculations were performed to determine the transverse stress wave response of the specimens. It was felt that the damage seen in the Shot 52, which was unfiltered, might be due to the stress waves generated in the silica coating due to the absorption of the low energy X-rays and UV. The stress wave transit time through the silica is very short (~0.01 nsec), and therefore the calculation was only run to 2 ns which would allow for many stress wave transit times through the silica layer to occur. Figure 13 shows the calculated peak stress envelopes for Shots 52 and 57 run to 2 nsec. The silica coating was completely removed in Shot 52 and intact in Shot 57. There is some very early time noise in Shot 52, but the trend indicates that the generated peak tensile stresses at the silica/gold interface could be nearly a factor of two larger in Shot 52 than in Shot 57. Tensile stress levels of about 0.2 kbars may be sufficient to fail the interface. Spall or delamination of the silica layer is probably the cause of the silica coating layer removal.

Summary

Six tests were successfully performed at the Omega facility on 14 July 2006. The Omega X-ray output was well behaved. X-ray characterization data and diagnostics were measured and interpreted. The optical specimens were successfully tested and a range of responses was obtained. Photomicrographs indicate that the level of damage ranged from none to complete removal of the SiO_x protective layer due to stress wave failure of the interface. The specimens underwent posttest characterization and reflectivity measurements. PUFFTFT analyses were completed and the specimen's thermal lateral stress and transverse stress conditions were calculated and interpreted. No major anomalies were detected. Comparison of the pre- and posttest reflective measurements coupled with the TFCALC analyses proved invaluable in guiding the analyses and interpreting the observed damage.

The Omega facility will provide a high quality facility for performing evaluation of optical coatings and coupons. The spectrum simulates the energy distributions of low keV blackbody sources. The pulses are short compared to currently available facilities but seem to be reproducible. The range of fluences is sufficient to stress and fail mirror coating concepts under consideration. The facility is clean enough that optical specimens could probably be tested without a debris shield. However, thin beryllium filters not only eliminate undesirable UV and low energy X-rays but also provide coating specimen protection from any generated debris.

Acknowledgements

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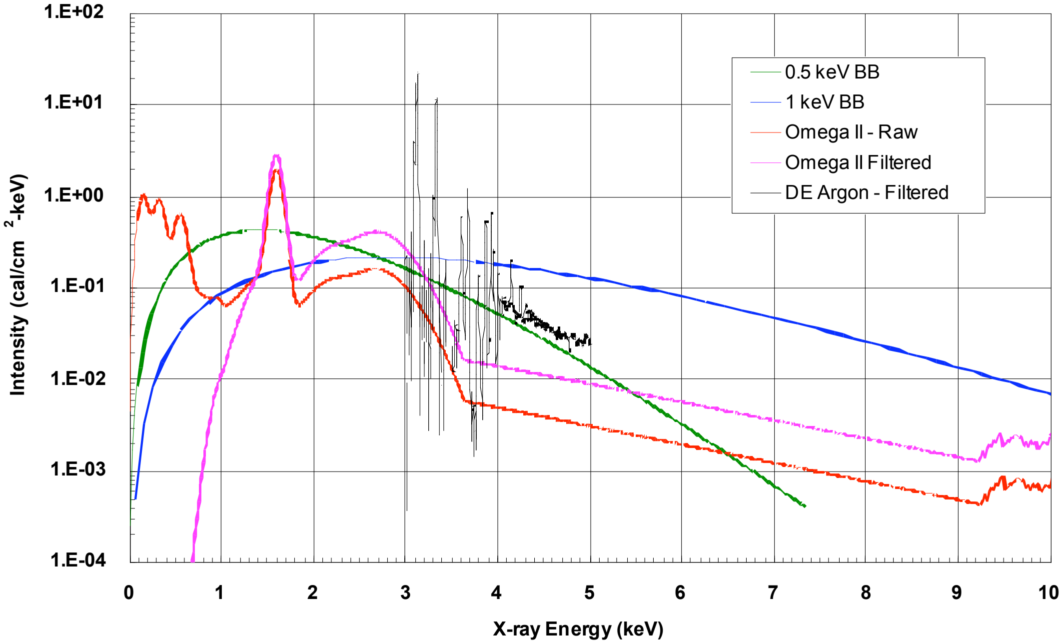

Figure 1. Omega II Spectra Compared to 0.5 and 1 keV Blackbodies and SXR Argon

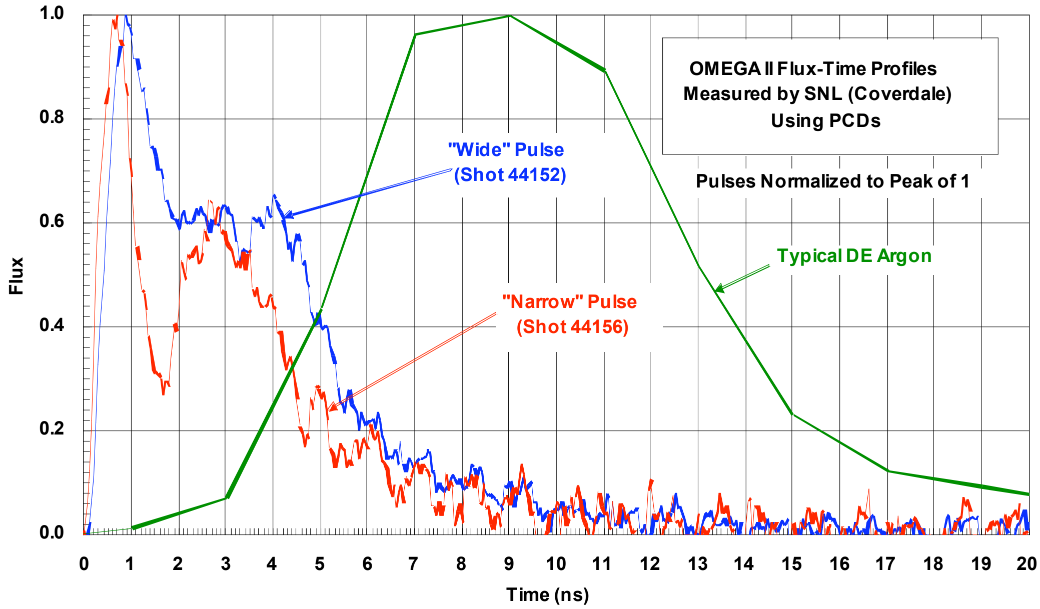

Figure 2. Preliminary Omega II Measured Flux-Time Profiles.

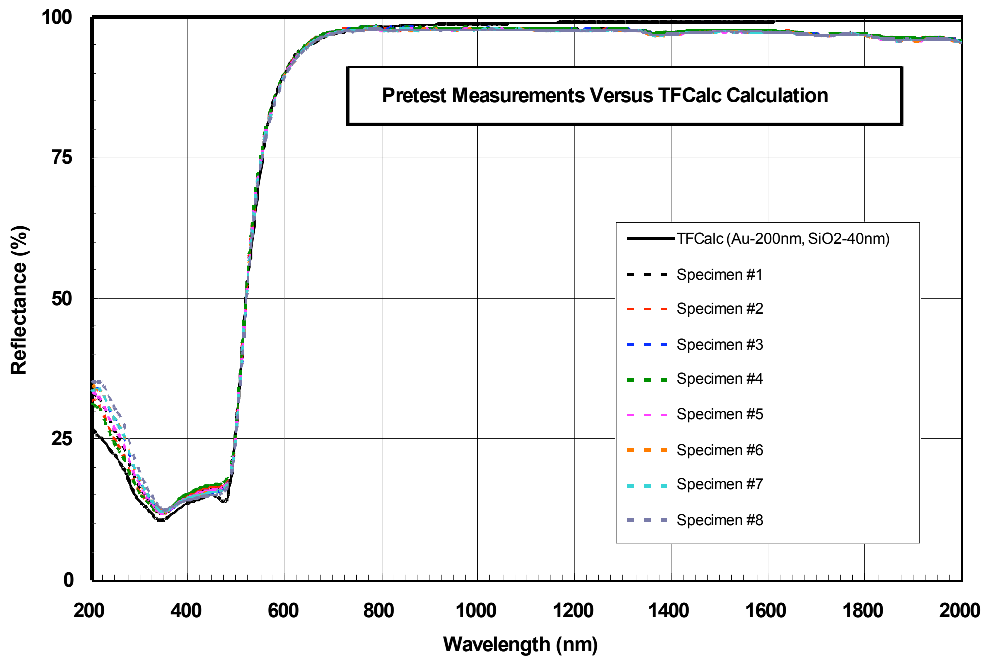

Figure 3. Pretest Reflectance Measurements Compared to TFCALC.

Table 1. Omega II Test Matrix.

Final Test Matrix

14 July 2006

Shot	Spectrum	Filter	Fluence on Specimen (cal/cm^2)	Range to Specimen (cm)	Comments
1	51	None	90% of SMF* = 0.0264	70.3	Obtain data near SMF. Confirm analysis results. Ensure specimen does not fail from substrate fra cture. Determine "cleanliness" of facility test environment.
2	50	1 mil Be	90% of SMF = 0.0427	35.2	Ensure Be foil survivability and ability to provide clean environment. Compare results with Shot 1. Confirm analysis results.
3	50	2 mil Be	110% of SMF = 0.0587	25.5	Generate failed specimen. Ensure failure mode is gold melt. Validate model.
4	50	1 mil Be	120 % of SMF = 0.0450	30.5	Home in on specimen melt fluence.
5	51	1 mil Be	120 % of SMF = 0.0450	29.3	Compare 3 ns spectrum results with 1 ns (Shot 4)
6	50	2 mil Be	105% of SMF = 0.0561	26.1	Home in on specimen melt fluence from the high side. Compare damage with Shot 3. Provide a second confirmatory shot of gold mirror softness.
7	50	3 mil Be	95% of SMF = 0.0547	23.5	Compare results with Shot 4. Validate filter models.

*SMF = Specimen Melt Fluence

Table 2. July Test Series Experimental Details.

Shot	Yield (cal/ster)	Range (cm)	Pulse Type	Fluence on Filter (cal/cm^2)	Be Filter (mils)	Fluence on Specimen (cal/cm^2)
52	144.81	70.3	Long	0.0293	0	0.0293
53	165.67	35.2	Short	0.1337	1	0.0452
54	215.80	25.5	Short	0.3319	2	0.0768
56	214.76	30.5	Short	0.2309	1	0.0823
57	116.01	29.3	Long	0.1351	1	0.0410
58	167.93	26.1	Short	0.2465	2	0.0599

Table 3. Visual Observations of Posttest Photomicrographs.

Shot	Specimen	Visual Observations
52	1	Outer layer(s) completely removed over entire exposure area. Based on reflectance data, the silica layer has been removed. Analyses and exposure area edge description suggest mechanical removal, not melt or vaporization. Gold layer appears to be intact
53	6	One very small area shows removal of silica (folded back on itself indicating mechanical interface failure. Remaining silica and gold coatings remain intact and undamaged
54	5	No damage to either coating is evident.
56	8	Silica coating removal at several areas. These areas appear to be a small percentage of the total exposed area. Close-ups of damaged area shows solid silica coating debris and folding of the layer at numerous locations.
57	4	Beryllium filter fractured and failed on this shot. Specimens shows debris on the surface.
58	7	No damage to either coating is evident.

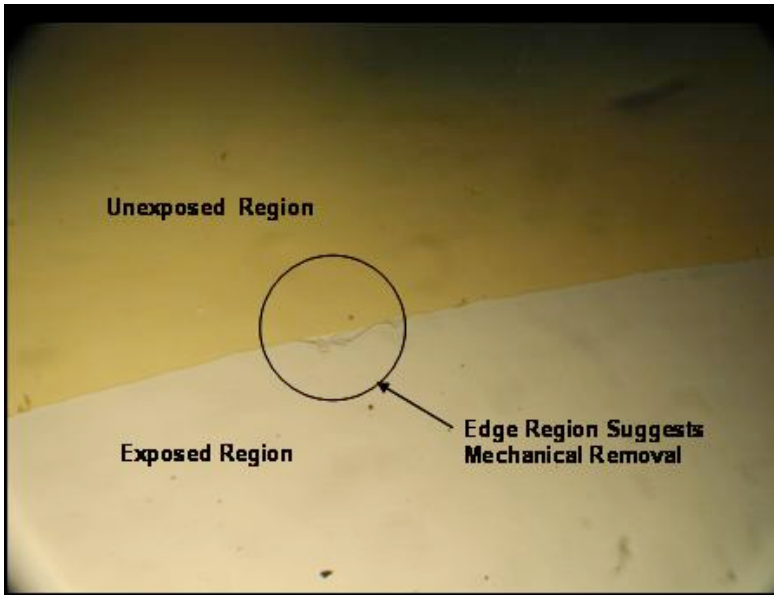

Figure 4. Photomicrograph of Specimen 1 (Shot 52).

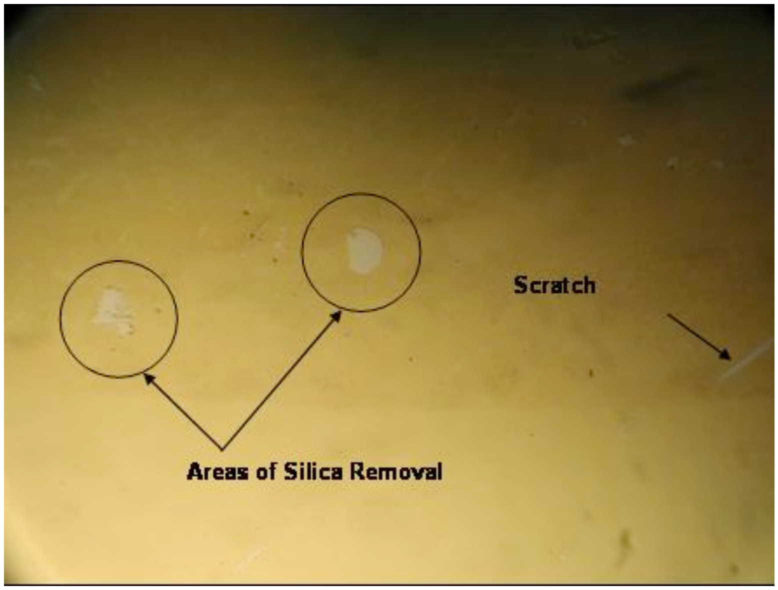

Figure 5. Photomicrograph of Specimen 8 (Shot 56)

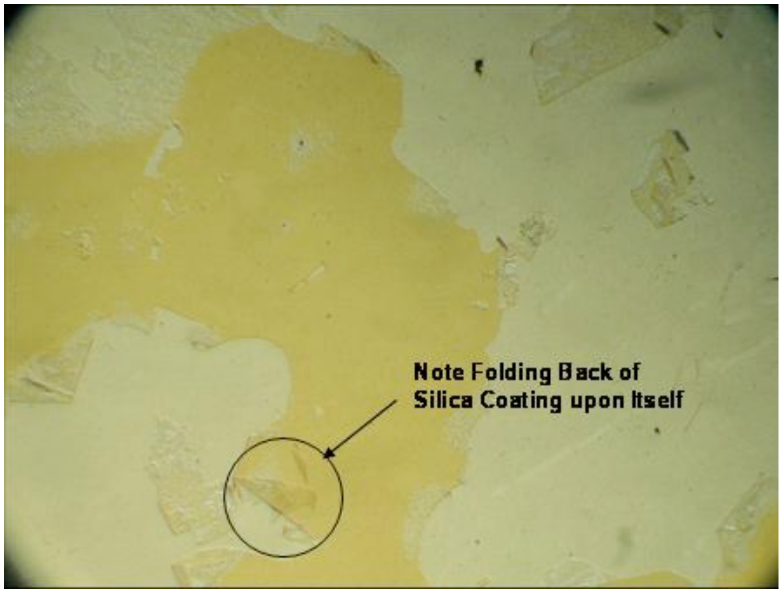

Figure 6. Close-Up of Damage on Specimen 8

Figure 7. Photomicrograph of Specimen 5 (Shot 54)

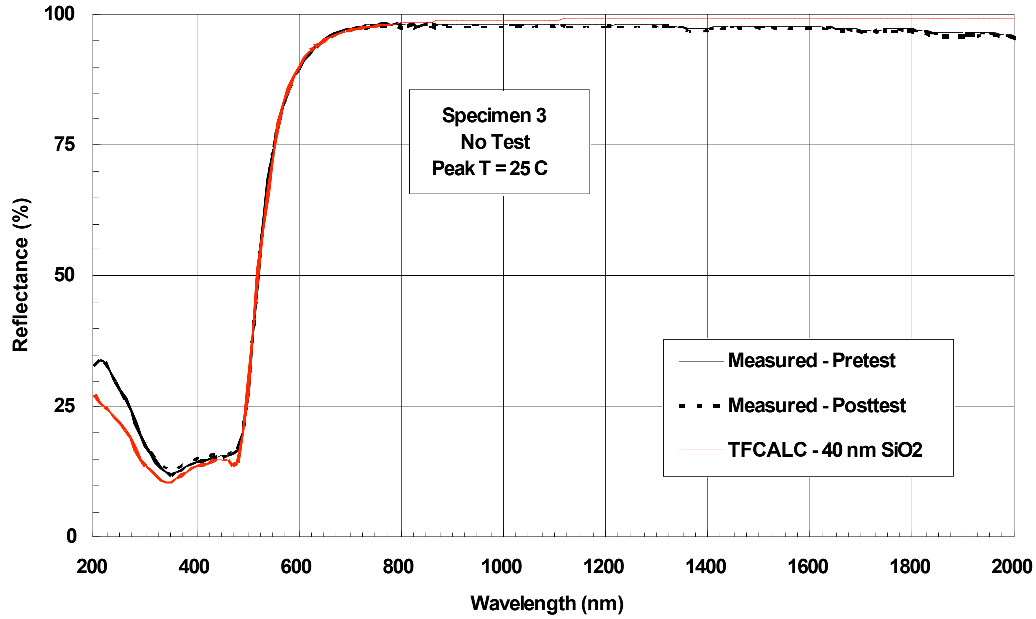

Figure 8. Pre- and Posttest Reflectance for Specimen 3 (untested)

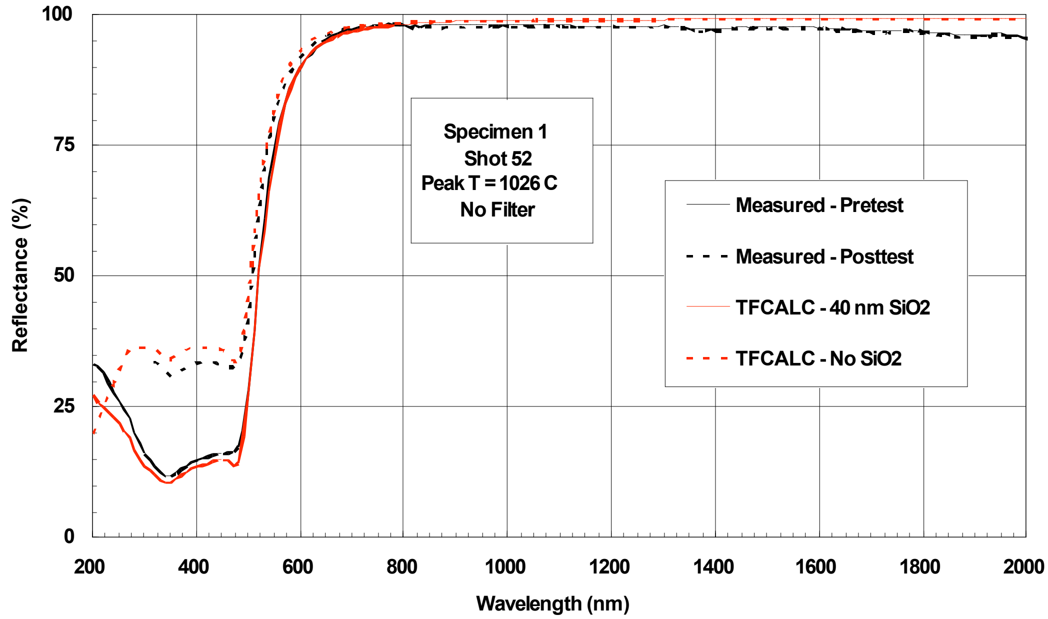

Figure 9. Pre- and Posttest Reflectance for Specimen 1 (Shot 52) and TFCALC Analysis With and Without the Silica Coating

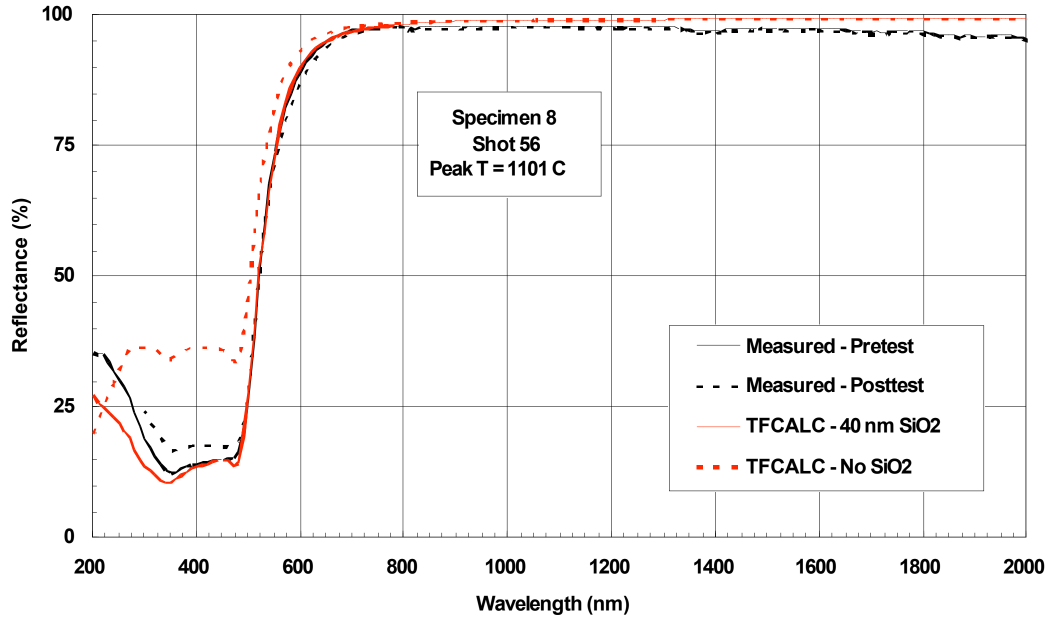

Figure 10. Pre- and Posttest Reflectance for Specimen 8 (Shot 56) and TFCALC Analyses

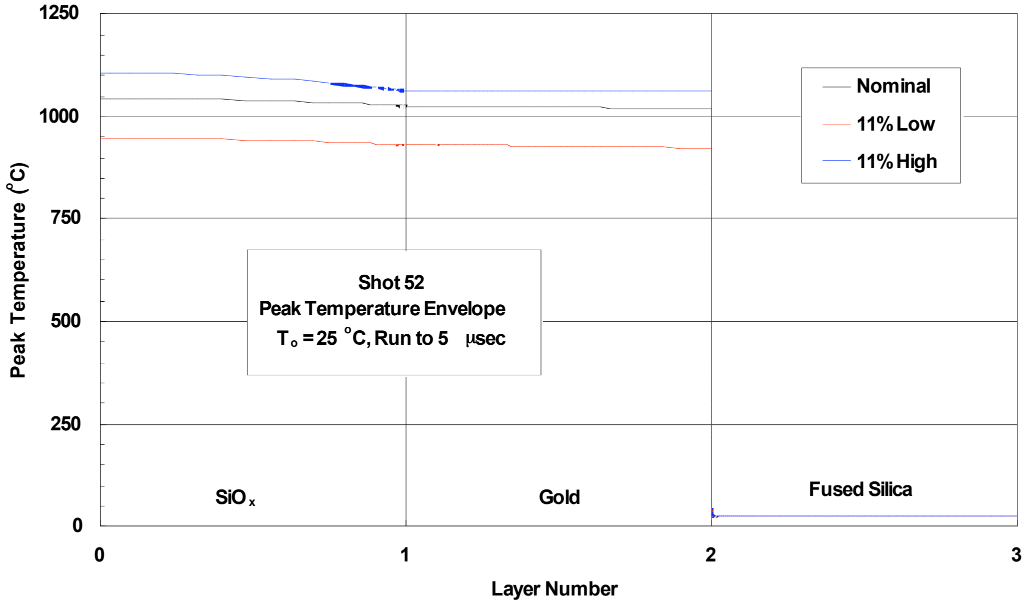

Figure 11. Calculated Peak Temperature Envelope for Specimen 1 (Shot 52)

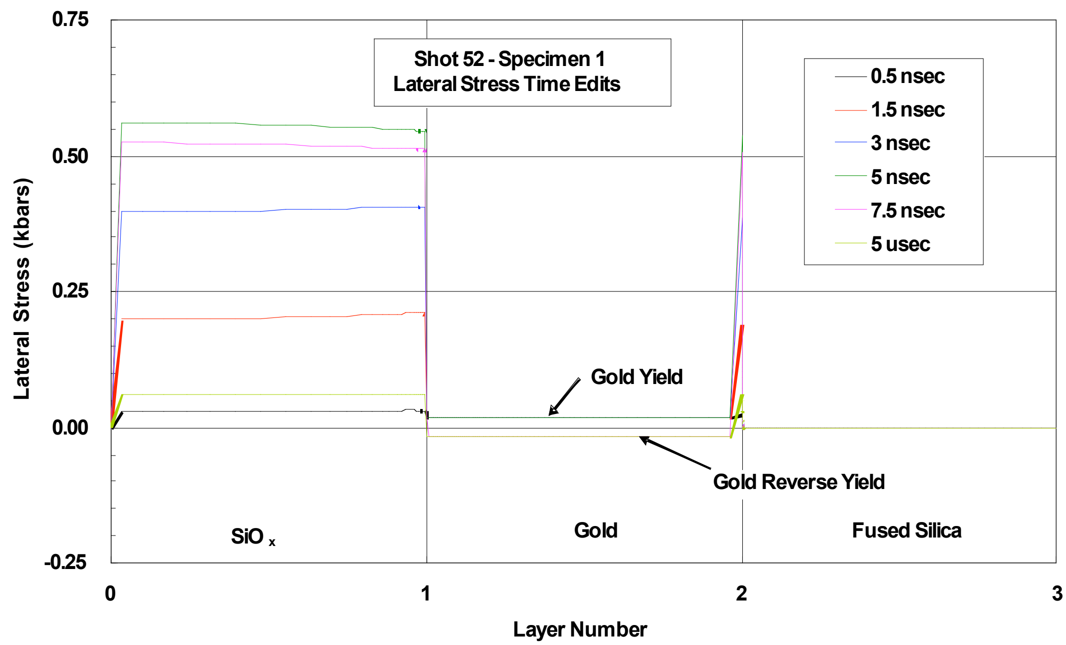

Figure 12. Calculated Lateral Stress Profiles for Specimen 1 (Shot 52)

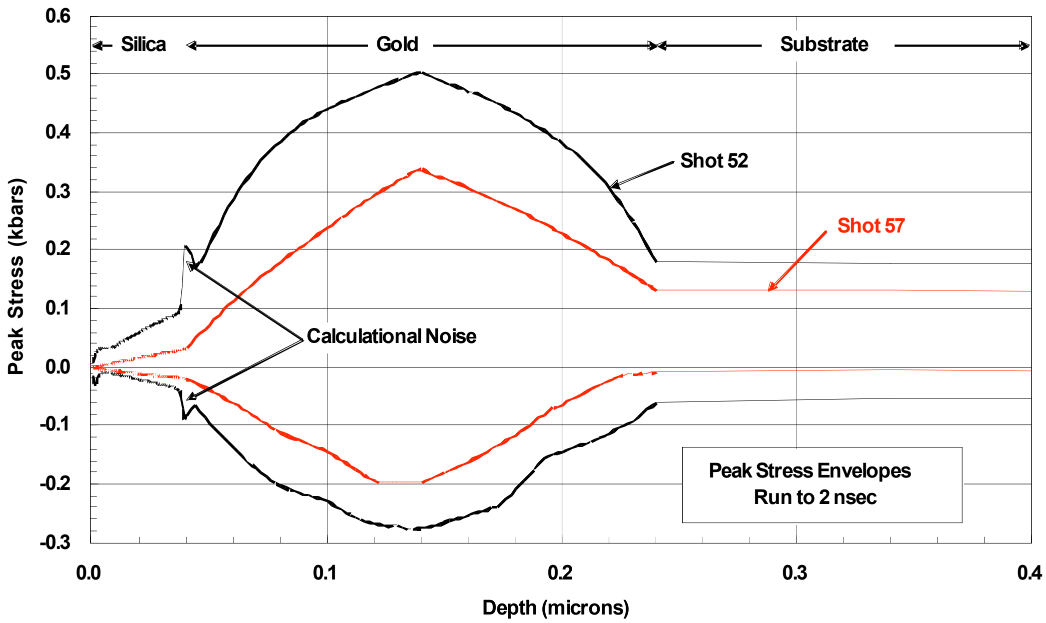

Figure 13. Peak Stress Envelopes Calculated for Shots 52 and 57